Towards Visual Arctic Terrain Assessment

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Abstract Many important scientific studies, particularly those involving climate change, require weather measurements from the ice sheets in Greenland and Antarctica. Due to the harsh and dangerous conditions of such environments, it would be advantageous to deploy a group of autonomous, mobile weather sensors, rather than accepting the expense and risk of human presence. For such a sensor network to be viable, a method of navigating, and thus a method of terrain assessment, must be developed that is tailored for arctic hazards. An extension to a previous arctic terrain assessment method is presented, which is able to produce dense terrain slope estimates from a single camera. To validate this methodology, a set of prototype arctic rovers have been designed, constructed, and fielded on a glacier in Alaska.

1 Introduction

An important aspect of autonomous field robotic navigation is terrain assessment. When an autonomous agent is deployed in unstructured, natural environments, the exact condition of the environment cannot be known ahead of time. Instead, the agent must assess the terrain condition locally, then revise its navigation plan as necessary. Much of the literature in the area of terrain assessment focuses on desert environments, arising from the needs of NASA's Mars rovers and the first two DARPA Grand Challenge events [2, 4, 6].

In contrast, little work has focused on navigating in arctic environments, despite the scientific importance of such areas. Though many scientists believe the condition of the giant ice sheets in Greenland and Antarctica are a key to understanding global climate change, there is still insufficient data to accurately predict the future behavior of those ice sheets. While satellites are able to map the ice sheet elevations with increasing accuracy, data about general weather conditions (i.e. wind speed, barometric pressure, etc.) must be measured at the surface.

In order to obtain measurements, human expeditions must be sent to these remote and dangerous areas. Alternatively, a group of autonomous robotic rovers could be deployed to these same locations, mitigating the cost, effort, and danger of human presence. For this to be a viable solution, a method for navigating in the arctic, and thus of assessing arctic terrain, must be developed. This paper extends the work presented in [10], creating dense slope estimates of the terrain from a single camera. Sect. 2 briefly describes the types of terrain likely to be encountered in the arctic regions of Greenland or Antarctica. Sect. 3 details the slope assessment algorithm. A set of prototype arctic rovers have been designed and constructed. A description of the units and the field tests conducted is presented in Sect. 4. The slope estimate results from the field tests are shown in Sect. 5. Finally, conclusions and future work are discussed in Sect. 6.

2 Environment

Despite being covered by snow, arctic regions present a large assortment of terrain challenges, a small sample of these are shown in Fig. 1. Large quantities of fresh surface snow can be present during certain times of the year. This fresh snow is soft, creating a potential sinking hazard for wheeled vehicles. The soft snow is also more readily melted, causing a dimpling of the surface, referred to as “sun cups,” which can span 0.5 meters or more. Over time the winds harden the snow surface making it more amenable to locomotion. However, these same winds also sculpt the snow into dune-like structures that can be as large as one meter, again impeding motion. The underlying ice sheet is also responsible for several types of terrain hazards. As the ice sheet flows, forces build due to differential velocities of different ice sections. These forces can cause nearly vertical fractures in the ice known as crevasses. Crevasses can be as deep as 30 meters and are often covered with snow, making their detection all the more difficult. A narrow crevasse is shown in Fig. 1(c), which becomes obscured by snow toward the top of the image. In the thinner regions of the ice sheet, the surface is affected by the underlying mountains, causing significant local-scale elevation changes. Even on seemingly flat terrain, the actual snow depth can change drastically, with the ice sheet exposed in some locations, and covered by several meters of snow in others.

3 Slope Assessment

The slope estimation technique presented in [10] divided the image into large blocks in which the surface texture was analyzed. A single slope estimate was produced which was aligned with the predominate surface texture direction. The resulting estimates, although noisy, were shown to be representative of the actual slope within a simulated environment, and sufficient input for a slope-avoidance control scheme.

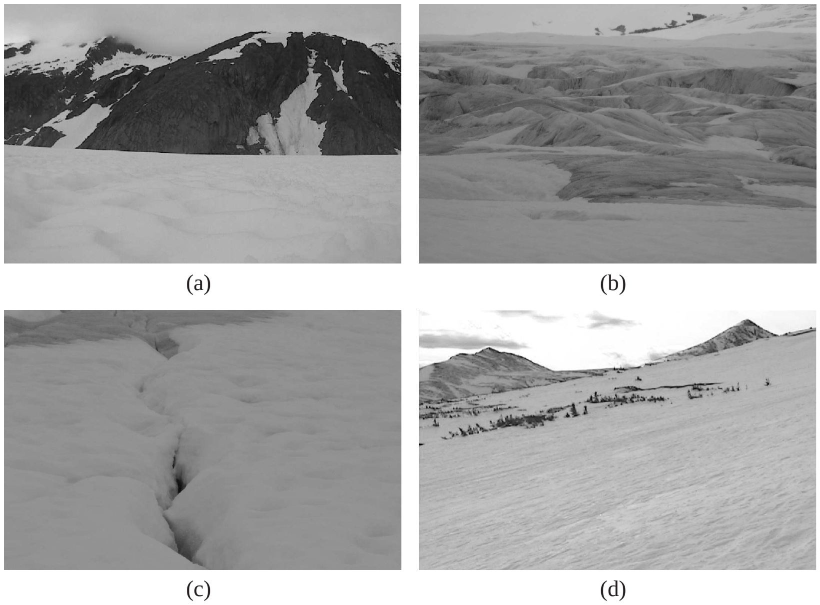
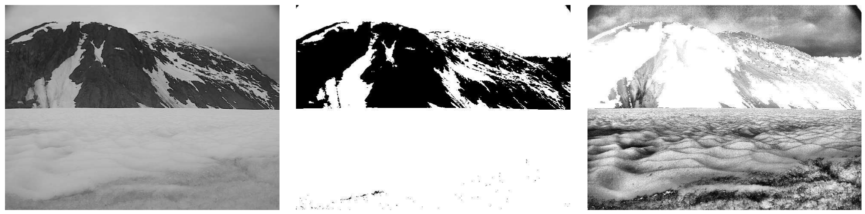


Fig. 1 Images from the top of Mendenhall Glacier, Alaska showing (a) visible sun cups, (b) a large section of exposed ice sheet, and (c) a small crevasse visible through the snow. (d) An image from an analogous site on the Arikaree Glacier, Colorado showing the potential steep slopes in glacial terrain.

Presented below is an improvement upon this algorithm which results in a set of dense slope estimates for the scene.

In images of arctic terrain, the surface texture has very low contrast. In order to analyze this texture, the foreground contrast must first be boosted. An adaptive, nonlinear preprocessing stage has been introduced, originally formulated to enhance x-ray images and CT scans [9]. Contrast limited adaptive histogram equalization (CLAHE) separates the image into different contextual regions. Within each region, a histogram equalization procedure is calculated. To prevent over-enhancement of local areas, a contrast limit is imposed. In effect, this applies an upper bound to the slope of the gradient at a specific location, resulting in smoothly varying contrast.

However, the presence of image distractors, such as background mountains, have an adverse effect on both the contrast enhancement and the subsequent slope estimates. A method of histogram thresholding, presented in [10] has been applied here. It is assumed that the majority of the image is filled with the snowy region. Consequently, in the histogram of the image, the largest peak should be associated with the grayscale values of the snow. An adaptive threshold based on the boundaries of this peak produces an image mask which can effectively separate the region of interest from unwanted objects and areas. Fig. 2 shows the results of the mask and contrast enhancement on a single exemplar glacial image. For the first time, the



(a) (b) (c)

Fig. 2 (a) An image from Mendenhall Glacier, Alaska, (b) the mask produced by the histogram threshold procedure which separates the region of interest from the background objects, and (c) the results of the CLAHE contrast enhancement of the masked image. For the first time, the underlying structure of the scene is clearly visible.

underlying scene structure is clearly visible. Although, the image noise has clearly been amplified as well.

The enhanced snow texture exhibits small-scale directional details, which are visually similar to those of fingerprints. In the area of fingerprint enhancement, where it is desired to find and follow the small ridge details of a print, it is common to create an orientation image to aid in the processing [3, 5]. A least square estimate procedure for calculating this orientation is presented in [3]. In a similar fashion, the final slope estimate is produced by finding the least square estimate of the dominant Fourier spectrum direction in a neighborhood around each pixel.

To calculate the orientation of a given pixel, (i,j), the image gradient within a neighborhood of that pixel is first calculated. Then the two component vectors, $v_\mathbf{x}$ and $v_\mathbf{y}$, are generated, as described in Equations 1 and 2. The orientation, θ, is then defined as the least squares solution to Equation 3. The entire slope calculation process can be processed in real-time.

$$v_\mathbf{x}(i,j) = \sum_{neighborhood} 2\partial_x(u,v)\partial_y(u,v) \tag{1}$$

$$v_\mathbf{y}(i,j) = \sum_{neighborhood} \partial_x^2(u,v) - \partial_y^2(u,v) \tag{2}$$

$$\theta(i,j) = \frac{1}{2}\tan^{-1}\left(\frac{v_\mathbf{y}(i,j)}{v_\mathbf{x}(i,j)}\right) \tag{3}$$

4 Field Tests

To validate the slope assessment algorithm, three prototype mobile weather sensor nodes were constructed. The rovers, referred to as “Sno-motes”, were subsequently fielded on a frozen lake near Wapakoneta, Ohio and on Mendenhall Glacier in Juneau, Alaska.

4.1 Sno-mote Mk1

A $1/10$ scale snowmobile chassis was selected for the prototype platform, endowing the rover with an inherent all-terrain drive system. The platform was modified to include an ARM-based processor running a specialized version of Linux. The motherboard offered several serial standards for communication, in addition to wifi and bluetooth. A daughterboard provided an ADC unit and PWM outputs for controlling servos. The drive system was modified to accept PWM motor speed commands, and the steering control was replaced with a high-torque servo. For ground truth position logging, a GPS unit connects to the processor via the bluetooth interface, while robot state and camera images are sent directly to an external control computer via the wifi link. To simulate the science objectives of the mobile sensor, a weather-oriented sensor suite was added to the rover. The deployed instrument suite includes sensors to measure temperature, barometric pressure, and relative humidity.

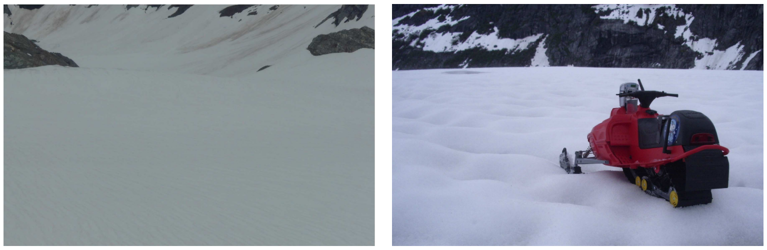
4.2 Alaska Test Site

The three “Sno-mote” platforms and related equipment were shipped to Juneau, Alaska for field testing. Two potential test sites were selected based on the relevance of weather data, the similarity of the terrain to arctic conditions, and logistics. Site 1, Lemon Creek Glacier, has been the subject of annual mass balance measurements since 1953 as part of the Juneau Icefield Research Program (JIRP) [8], making weather measurements in this area particularly relevant. The second site, Mendenhall Glacier, is one of Alaska’s most popular tourist attractions [7]. The current public interest of this particular site makes additional information valueable. Both sites are only accessible via helicopter.

Helicopter travel to glacial areas is heavily dependent on the weather conditions, particularly low cloud deck heights. This presents a dangerous “white out” situation for the helicopter pilot in which the snow-covered peaks, the ground of the landing site, and the sky are all indistinguishably white. During the course of our flight to Lemon Creek such a situation was determined to exist, forcing the group to abandon the site for the day. A few images were acquired from this site before departure, a sample of which is shown in Fig. 3(a).

The weather conditions preventing travel to either of the test site finally lifted on Day 4, allowing travel to Mendenhall. The site surface is visually flat and covered with snow, though there are sections of the terrain where the underlying ice sheet is exposed. Despite the flat appearance, the snow varied in depth from a few centimeters to over a meter. This snow was deposited recently and was quite soft. Upon arrival at the site, a test area was explored with ice-axes to ensure it was safe. Cracks in the underlying ice, called crevasses, are often completely concealed by surface snow.

The rovers were driven manually to assess the mobility performance in the different snow conditions present. During these traverses it was discovered that the plat-



(a) (b)

Fig. 3 (a) A sample of images acquired from Lemon Creek Glacier, Alaska before weather conditions forced the site to be abandoned for the day. Some of the underlying mountain range is visible though the glacier surface, but the terrain is predominately white, with the slope characteristics almost invisible. (b) A Sno-motes deployed at Mendenhall Glacier in Juneau, Alaska.

form suffered from stability issues. Due to the narrow track footprint in the rear, the chassis would often roll sideways when attempting to navigate perturbations in the snow surface. Additionally, the snowmobile would sink in the fresh snow, causing the DC drive motor to stall from excess torque. Due to the chassis limitations, a set of short traverses were performed in selected locations. During these traverses, the local temperature, barometric pressure, relative humidity, GPS location, and camera images were all logged at 2 Hz and timestamped to ensure proper off-line reconstruction and analysis. Fig. 1(a) - 1(c) show some sample images acquired at the Mendenhall test site.

4.3 Sno-mote Mk2

The main reason tracked vehicles are used for snow traversal is the large area of the track distributes the vehicle weight, allowing it to “float” on the surface. Possibly the most capable snow vehicle is the “Alpina Sherpa” [1], which was designed with two tracks to further reduce the applied pressure. Due to the discovered mobility issues with the original platform, a set of chassis modifications were designed and implemented, with inspiration taken from the “Sherpa”. The original front suspension mechanism was replaced by a passive double-wishbone system, increasing the ski-base over 30%. The rear track system was replaced with a custom, dual-track design, which both widened the rear footprint and effectively doubled the snow contact surface area. A 500 W brushless motor and high-current speed controller drive the new track system. The overall increase in the platform width drastically improved the platform’s stability and role characteristics. Fig. 4 shows the modified chassis, as deployed on a frozen lake near Wapakoneta, Ohio.

Fig. 4 The modified chassis of the second generation “Sno-mote” deployed near Wapakoneta, Ohio. Clearly visible is the new dual-track drive system.

4.4 Ohio Test Site

A test site near Wapakoneta, Ohio was selected to verify the performance of the new chassis. The site was blanketed with 8-12 inches of fresh snow next to a frozen lake. Several long traverses were conducted, which transitioned from land to lake several times. During these traverses, the GPS location and camera image were logged at 15 Hz and timestamped. The lake bank consisted of irregularly spaced large rocks, between which large amounts of snow had collected, forming a drivable incline between 10° and 30°.

The improved chassis performed well during the tests, never rolling, even when negotiating a path between rocks up a 20° slope. While it was still possible for the chassis to loose traction, especially in very soft snow or up steep inclines, the new drive motor was never forced into a stall condition. However, one unexpected observation from these test was that the control computer, which consisted of a consumer-grade laptop, ceased to operate when its temperature dropped below 20°F. The “Sno-mote” control computer and hardware were unaffected by the cold.

5 Results

The slope estimation algorithm, presented in Sect. 3, has been applied to the images acquired during the field tests. For comparison, the original slope estimate technique, presented in [10], has also been calculated. The results of both techniques are shown in Fig. 5. While both methods show the general regions in front of the camera to be flat, the denser information of the proposed method is better able to capture the smaller scale surface trends. This is particularly evident in the lower left of the images in Fig. 5(a) and 5(b). The proposed method accurately indicates the slopes around a depression in the snow, whereas the original method provides only a single, slightly upward slope indication. Also, the new method is able to handle the ice as well as the snow image textures. The original method provides spurious measurements in the ice regions that do not reflect the true terrain grade. In the Ohio images, Fig. 5(c) and 5(d), the original method completely ignores the small dune

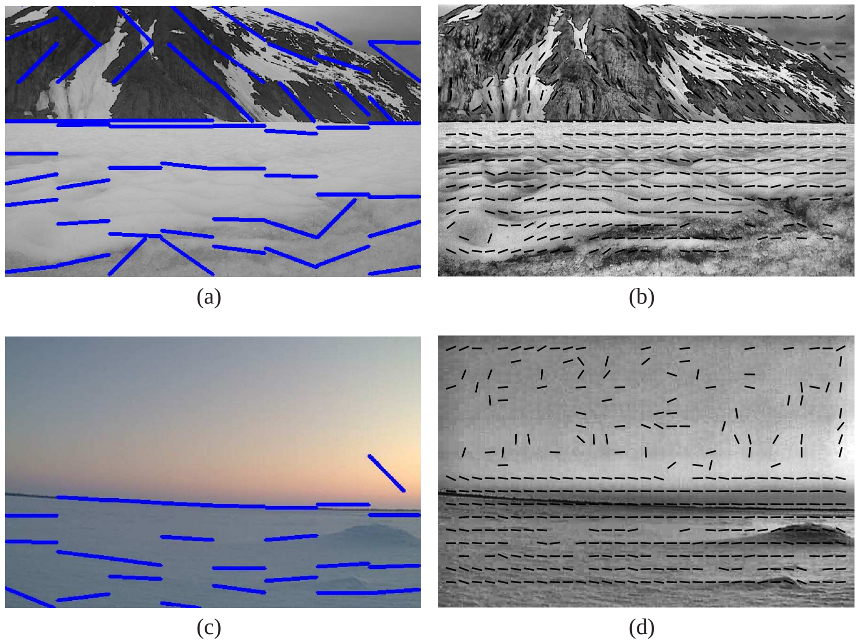


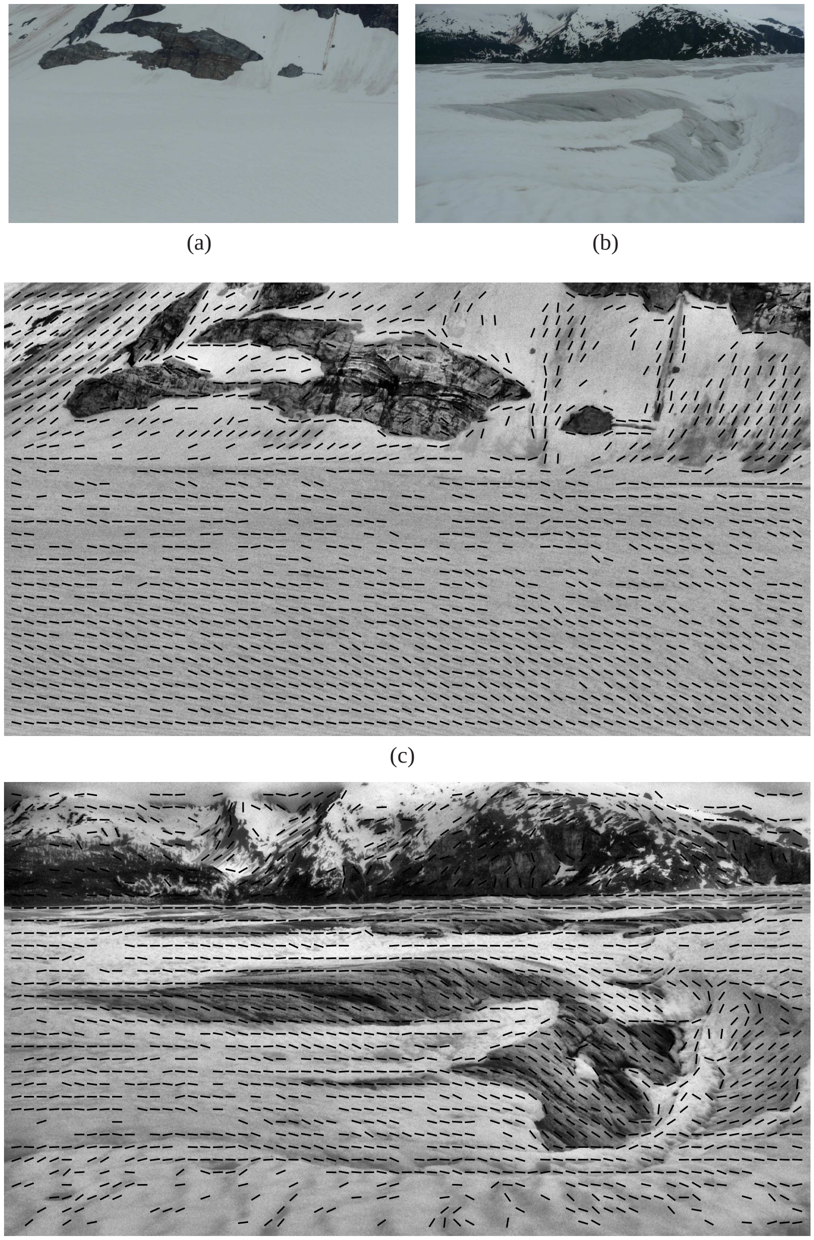
Fig. 5 (a, b) An image taken during the field tests at Mendenhall Glacier, Alaska has been processed by the original slope estimation procedure and the proposed method. Similarly, (c, d) an image from the Ohio field tests has been processed by both methods. The proposed method produces much denser estimates that are better able to capture smaller scale surface details.

structures, whereas the new method does indicate the sloping regions on either side of both structures.

Examples of processed arctic terrain are provided in Fig. 6. In the first image set from Lemon Creek Glacier, the terrain grade in the original image is virtually invisible. Yet, the estimate process is able to provide dense estimates, even in the areas that originally seemed uniformly white. The second pair of images illustrates a large crevasse on Mendenhall Glacier. The slope estimation process is able to handle both the snow and exposed ice textures without modification. The estimates provided clearly show the snow and ice sloping into the mouth of the crevasse, while a relatively safe area exists in the far left.

6 Conclusions

When navigating in arctic terrain, the local terrain slope is an important factor when determining traversabilty. Vehicle limitations may impose terrain grade limits, or local areas of steep decent may imply hazards. A purely visual slope estimation



(a) (b)

(c)

(d)

Fig. 6 Images (a) and (c) show an original image from Lemon Creek glacier, and the enhanced and processed version, respectively. Despite the surface texture being nearly invisible in the original image, the slope estimation process is able to produce dense, visually consistent slope measurements. Images (b) and (d) show an image of a large crevasse at Mendenhall glacier and the resulting slope estimates. The slope profiles in (d) clearly show the elevation changes at the edge of the crevasse.

technique has been presented which creates dense slope estimates from a single image, even in the inherently low contrast environment of the arctic.

A set of prototype rovers have been constructed, based upon a snowmobile design, and fielded on a frozen lake in Ohio, as well as on Mendenhall Glacier in Juneau, Alaska. A sample of the slope estimation results from these field tests have been included. Qualitatively, the results appear consistent with human perceived slope determinations, and are an improvement over a previously presented method, both in terms of estimate density and slope misclassification.

In the future, these slope estimates will be developed into a full traversabilty assessment, were drivable terrain is classified as safe and terrain hazards are labeled. This would, in turn, be used by the navigation and path planning system to plot safe trajectories.

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